

The Araucaria Project. OGLE-LMC-CEP-1718: An exotic eclipsing binary system composed of two classical overtone Cepheids in a 413-day orbit ¹

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ABSTRACT

We have obtained extensive high-quality spectroscopic observations of the OGLE-LMC-CEP-1718 eclipsing binary system in the Large Magellanic Cloud which Soszynski et al. (2008) had identified as a candidate system for containing two classical Cepheids in orbit. Our spectroscopic data clearly demonstrate binary motion of the Cepheids in a 413-day eccentric orbit, rendering this eclipsing binary system the first ever known to consist of two classical Cepheid variables. After disentangling the four different radial velocity variations in the system we present the orbital solution and the individual pulsational radial velocity curves of the Cepheids. We show that both Cepheids are extremely likely to be first overtone pulsators and determine their respective dynamical masses, which turn out to be equal to within 1.5 %. Since the secondary eclipse is not observed in the orbital light curve we cannot derive the individual radii of the Cepheids, but the sum of their radii derived from the photometry is consistent with overtone pulsation for both variables.

The existence of two equal-mass Cepheids in a binary system having different pulsation periods (1.96 and 2.48 days, respectively) may pose an interesting challenge to stellar evolution and pulsation theories, and a more detailed study of this system using additional datasets should yield deeper insight about the physics of stellar evolution of Cepheid variables. Future analysis of the system using additional near-infrared photometry might also lead to a better understanding of the systematic uncertainties in current Baade-Wesselink techniques of distance determinations to Cepheid variables.

Subject headings: stars: Cepheids - stars: pulsation - stars: eclipsing binaries - galaxies: individual(LMC) - distance scale

1. Introduction

Classical Cepheids are distance indicators par excellence and a fundamental rung on the cosmic distance ladder, connecting our Milky Way galaxy to galaxies in the Local Group and beyond (Freedman et al. 2001; Gieren et al. 2005a, 2006; Pietrzynski et al. 2006; Riess et al. 2011). In order to render Cepheids even more robust and reliable distance indicators, it is imperative to understand their physical and evolutionary properties with the highest possible accuracy. In that context, it has been a breakthrough to find classical Cepheids in detached, double-lined eclipsing binary systems which permit a determination of their basic physical parameters much more accurately than what is possible for any single Cepheid star. In particular, the analysis of the OGLE-LMC-CEP-0227 system located in the Large Magellanic Cloud (LMC), containing a classical Cepheid pulsating with a period of 3.8 days together with a stable red giant in a 310-day orbit, has yielded for the first time a Cepheid mass and radius determination accurate to 1 %, and valuable independent insight on the p-factor needed for Baade-Wesselink-type analyses (Pietrzynski et al. 2010; Pilecki et al. 2013). A second eclipsing binary system in the LMC containing an even shorter-period classical Cepheid, OGLE-LMC-CEP-1812, was analyzed by Pietrzynski et al. (2011) and again yielded a very accurate measurement of the dynamical mass of the Cepheid. These two Cepheid mass determinations have gone a long way to solve the famous Cepheid mass discrepancy problem, leading to improved predictions of Cepheid masses from stellar pulsation and evolution theories. (Marconi et al. 2013; Prada Moroni et al. 2012).

In the present paper, we report on the confirmation of an even more exotic, and so far unique, eclipsing binary system in the LMC consisting of a *pair of classical Cepheids in a 413-day orbit*. The system, herein named OGLE-LMC-CEP-1718, was discovered

and identified as a *double Cepheid* by Alcock et al. (1995). Later Soszynski et al. (2008) found that it also exhibits eclipsing variability, but it was not yet clear if the two Cepheids were indeed gravitationally bound. Our spectroscopic observations of this double-lined system over the past years clearly show that the two Cepheids orbit each other, with the additional radial velocity variability of the Cepheids due to their pulsations superimposed on their orbital radial velocity curves. Evidently, the analysis of this system and the characterization of the physical properties of its coeval Cepheids holds great promise to deepen our understanding of Cepheid physics and evolution.

In this paper, we present spectroscopic observations of OGLE-LMC-CEP-1718 and extract the orbital radial velocity curves of the two components of the system and the individual pulsational radial velocity curves of the Cepheids. We add new photometric data from OGLE III and OGLE IV surveys to that presented by Soszynski et al. (2008) to the radial velocity data to obtain the orbital solution as well as a determination of several physical parameters of the Cepheids, particularly their masses and pulsation modes.

2. Observations and Analysis

Using the MIKE spectrograph at the 6.5-m Clay Telescope at Las Campanas Observatory and the HARPS spectrograph attached to the 3.6-m telescope at the ESO La Silla Observatory we obtained 38 high-resolution spectra of OGLE-LMC-CEP-1718 (mean magnitudes $I=14.511$, $V=15.190$; Soszynski et al. 2008) between September 29, 2011 and December 12, 2013. Radial velocity determinations from these spectra were made using the Broadening Function Method (Rucinski 1992, 1999) implemented in the RaveSpan code (Pilecki et al. 2012). We analyzed the spectra in the range of 4125 to 6800 Å using as templates the theoretical spectra taken from the library of Coelho et al. (2005). The radial velocities determined in this way were typically accurate to 0.3 km/s and we have never seen any systematic difference between data obtained with MIKE and HARPS spectrographs. The measured radial velocities of both components are presented in Table 1.

In addition to these radial velocity data, we were able to use 1535 I-band measurements of the system collected by the OGLE Project (Udalski 2003) over many years, including data from the most recent OGLE III and IV surveys. The previous photometric analysis performed by Soszynski et al. (2008) had detected three periods- one describing the orbital motion of the two stars, and two additional magnitude variations due to the pulsations of two Cepheids with periods of 1.96 and 2.48 days. This was a promising indication that the Cepheids might be gravitationally bound, but it could also be a blend.

The analysis of the radial velocity dataset confirms the genuine spectroscopic binary nature of the system, with orbital motion of the two stars superimposed on the intrinsic radial velocity variations due to their pulsations. Knowing the pulsation periods from the photometry we were able to fit a complex model of orbital motion together with a pulsation variability for each object (see also Pilecki et al. 2013). This analysis clearly shows that the orbital period of the system is only half of the one originally assumed by Soszynski et al. (2008). This is a consequence of the fact that with the inclination and orbit orientation of the system, presented in Table 2 together with other orbital parameters derived in our orbital solution, only the primary eclipse is visible in the photometry whereas a possible secondary eclipse remains elusive and cannot be detected in the data. The absence of a secondary eclipse is fully consistent with the eccentricity and the other orbital parameters obtained in our analysis.

We were able to determine the four individual radial velocity curves which are superimposed in the data - the orbital radial velocities of the components of the system, and the pulsational radial velocity curves of the primary (P=1.96-day) and secondary (P=2.48-day) Cepheid components in the system. The orbital radial velocity curve of OGLE-LMC-CEP-1718, and the pulsational radial velocity curves of its two Cepheids are shown in Figures 1-3. The disentangling of the four different radial velocity curves is not yet perfect, but the small residuals from the fitted curves which are only slightly larger than the typical precision of the individual radial measurements demonstrate that the disentangling has been achieved with a high degree of accuracy with our code.

The pulsational radial velocity curves are both low-amplitude and approximately sinusoidal, as are the corresponding I-band light curves of the Cepheids which are shown in Figures 4 and 5. In Fig. 6 we show the orbital I-band light curve based on the full dataset, folded on the orbital period of 412.807 days.

3. Results and Discussion

From our orbital solution, we find that the masses of the Cepheids are 3.3 and 3.28 M_{\odot} , respectively, individually determined with an accuracy of 3 % (see Table 3). Because the high eccentricity error does not contribute to the evaluation of the mass ratio, it is determined with a much better accuracy. The analysis indicates that the two Cepheids in the OGLE-LMC-CEP-1718 system have equal masses to within ± 1.5 percent.

The very short pulsation periods suggest pulsation in non-fundamental modes. In Figure 7 we have plotted the positions of the two Cepheids on the I-band light curve

Fourier decomposition diagrams of Soszynski et al. (2008). The loci of both stars on these diagrams, particularly on the $R_{21} - \log P$ diagram, strongly suggest that both Cepheids in OGLE-LMC-CEP-1718 are pulsating in the first overtone mode.

This result can be checked in a different way. Since we cannot observe the secondary eclipse in the light curve, we cannot determine the individual radii of the Cepheids. However the analysis of the light curve does return the sum of the radii, in this case $52.5 \pm 1.5 R_{\odot}$. Assuming first overtone pulsation for the two Cepheids in OGLE-LMC-CEP-1718, we can calculate their expected radii from a period-radius relation calibrated for first overtone Cepheids. Using the observational relation given by Sachkov (2002), we obtain radii of $R = (26.1 \pm 2.5) R_{\odot}$ for the primary, and $R = (31.0 \pm 2.6) R_{\odot}$ for the secondary (longer-period) Cepheid, with the radii ratio of 1.19. These predictions are in excellent agreement with the predictions from the theoretical period-radius relation for first overtone Galactic Cepheids of Bono et al. (2001; 27 and 32 R_{\odot} , respectively). As the ratio is much better constrained than the radii themselves we have used it to calculate the individual radii of the Cepheids (using the known sum), obtaining $R_1 = 24R_{\odot}$ and $R_2 = 28.5R_{\odot}$ which is clearly consistent with the values from the given relation. If we assume fundamental mode pulsation for both Cepheids and use the fundamental mode Cepheid period-radius relation from Sachkov (2002) (which is very similar to other calibrations of that relation, e.g. Gieren et al. 1998), the expected sum of the radii is $44.0 \pm 0.3 R_{\odot}$, indicating that fundamental mode pulsation is much more unlikely. We have to note however, that in this case the calculations are based on the extrapolation as the periods of our stars are shorter than the shortest one among the stars used to obtain the relation.

Yet another argument supporting the first overtone pulsation hypothesis comes from the observed brightness of OGLE-LMC-CEP-1718. Using the fitted PL relations for first overtone Cepheids in the LMC from the OGLE project (Soszynski et al. 2008), the expected apparent magnitudes for the primary Cepheid are 15.439 and 16.110 in I and V bands, respectively, whereas for the secondary Cepheid the corresponding values are 15.104 and 15.786. This leads to expected total apparent magnitudes of both components of $I_{tot} = 14.506$ and $V_{tot} = 15.183$, respectively. The observed apparent magnitudes of the system are $I_{obs} = 14.511$ and $V_{obs} = 15.190$, in excellent agreement with the expected magnitudes if both Cepheids pulsate in the first overtone mode.

One possibility to reconcile the fact that both Cepheids in the system have the same masses, but different pulsation periods, would be the assumption that the primary, shorter-period Cepheid is actually pulsating in the second overtone mode. The observed period ratio of $1.96/2.48 = 0.79$ would be consistent with the hypothesis that the primary Cepheid is pulsating in the second overtone while the secondary Cepheid is a first-overtone

pulsator—a period ratio of about 0.8 is indeed commonly observed for double-mode 1O/2O Cepheids. However, in the OGLE database of Cepheids in the Magellanic Clouds (Soszynski et al. 2008) which contains the largest samples of Cepheids, among others about 100 single-mode second-overtone Cepheids and about 420 double-mode 1O/2O Cepheids, the largest known period of a second overtone Cepheid is 1.32 days (in the double-mode Cepheid OGLE-SMC-CEP-0305 in the Small Magellanic Cloud). This is very much shorter than the period of 1.96 days observed for the primary Cepheid in our OGLE-LMC-CEP-1718 system.

The largest known amplitude of the I-band light curve of a second overtone Cepheid is 0.138 mag (in the single-mode Cepheid OGLE-SMC-CEP-3509). Our object has a smaller amplitude of 0.097 mag (see Fig. 4), but the amplitude is decreased by the light from the secondary component through blending. Transforming the magnitudes to fluxes and removing the contribution of the secondary Cepheid, and transforming the flux back to magnitudes now yields an I-band amplitude of 0.231 mag for the short-period primary Cepheid in the OGLE-LMC-CEP-1718 system. This is much larger than any known amplitude of a second-overtone oscillation.

The shapes of the light curves cannot be directly compared because there are no second-overtone Cepheids with periods around 2 days. However, it can be stated that all second-overtone Cepheid light curves are more symmetrical than the one of the primary in our system, they are indeed nearly sinusoidal. Finally, the total luminosity of the OGLE-LMC-CEP-1718 system perfectly agrees with the assumption that the system consists of two first-overtone Cepheids, as already mentioned above. In conclusion, if the 1.96-day Cepheid in our system would indeed be a second overtone pulsator, it would be the longest-period and the largest-amplitude second-overtone Cepheid known in any galaxy. Given the large number of second-overtone Cepheids known to-date, it seems extremely unlikely that we found such an extreme object in the only eclipsing binary system consisting of two classical Cepheids that has been discovered so far.

Our conclusion then is that we have found a system composed of two classical Cepheids which have within a 1.5 % uncertainty identical masses, both stars are almost certainly pulsating in the first overtone mode, presumably have the same ages, but have substantially different periods and luminosities. It will be challenging for stellar evolutionary theory to explain the observed properties of these Cepheids, which will be the topic of a forthcoming study of our group.

4. Summary

We have presented the first confirmed eclipsing binary system with both components identified as classical Cepheids. These two variables orbit each other in an eccentric orbit with a period of 413 days. Strong evidence is presented that both variables are pulsating in the first overtone mode. The dynamical masses of both Cepheids are identical to within 2 percent and the absolute masses are determined with an accuracy of 3 percent. Both orbital light and radial velocity curves of the system and the pulsational light and radial velocity curves of the two Cepheids are very well determined from our data although improvement is possible and desirable.

The OGLE-LMC-CEP-1718 system, as the first confirmed eclipsing binary system containing two classical Cepheids, might well turn out to be a Rosetta stone for our deeper understanding of the pulsational and evolutionary properties of Cepheids. In response to this opportunity, and the challenges presented by the system we plan to improve the existing radial velocity data, and obtain observations of near- and mid-IR photometry which should help to better understand the physics of these variables. Near-infrared light curves for the two Cepheids in the system will in particular provide a unique opportunity to test the basic assumptions made in the near-infrared surface brightness technique (Fouqué & Gieren 1997; Gieren et al. 2005b; Storm et al. 2011) of the distance determination to Cepheids by taking advantage of the knowledge that both Cepheids are at the same distance.

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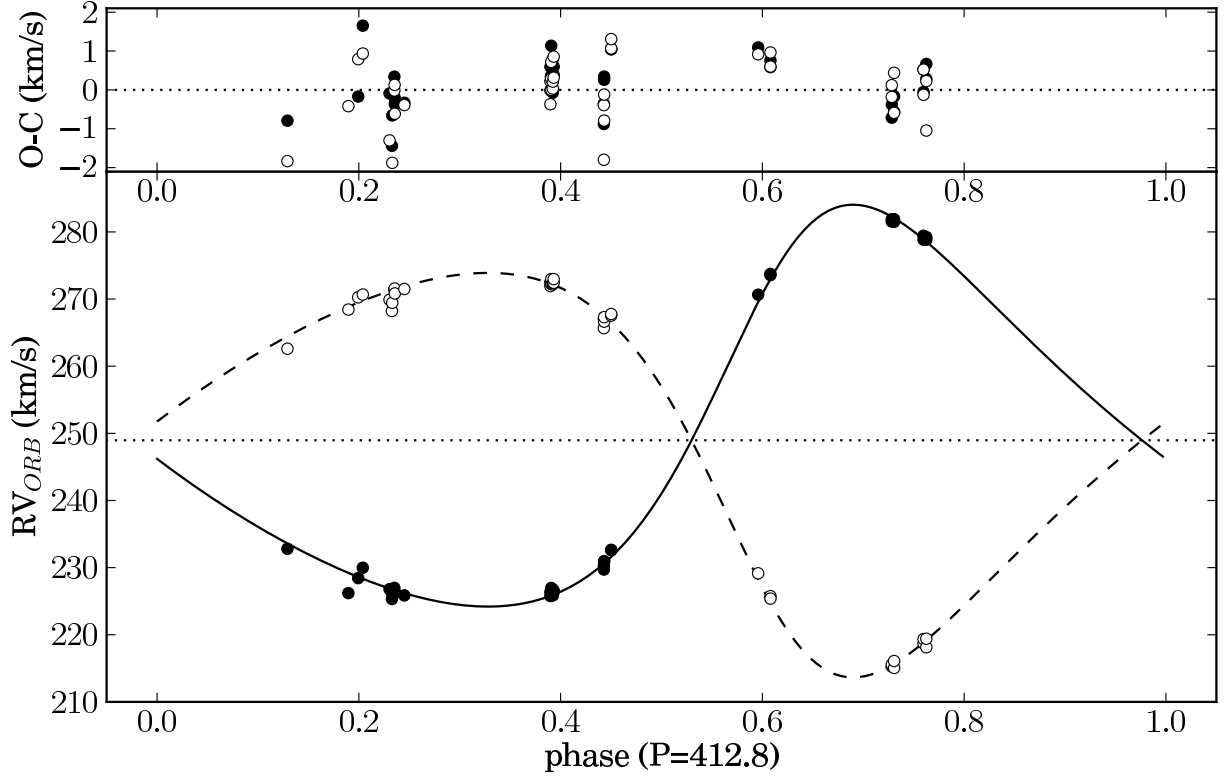


Fig. 1.— Orbital radial velocity curve of the OGLE-LMC-CEP-1718 system. Filled circles denote the primary component (the $P=1.96$ day Cepheid), open circles the secondary component (the $P=2.48$ day Cepheid). The pulsations of both Cepheids were removed from the observed radial velocities, yielding the pure orbital motion of the stars. The plot is based on the 38 individual radial velocity observations of the system reported in Table 1.

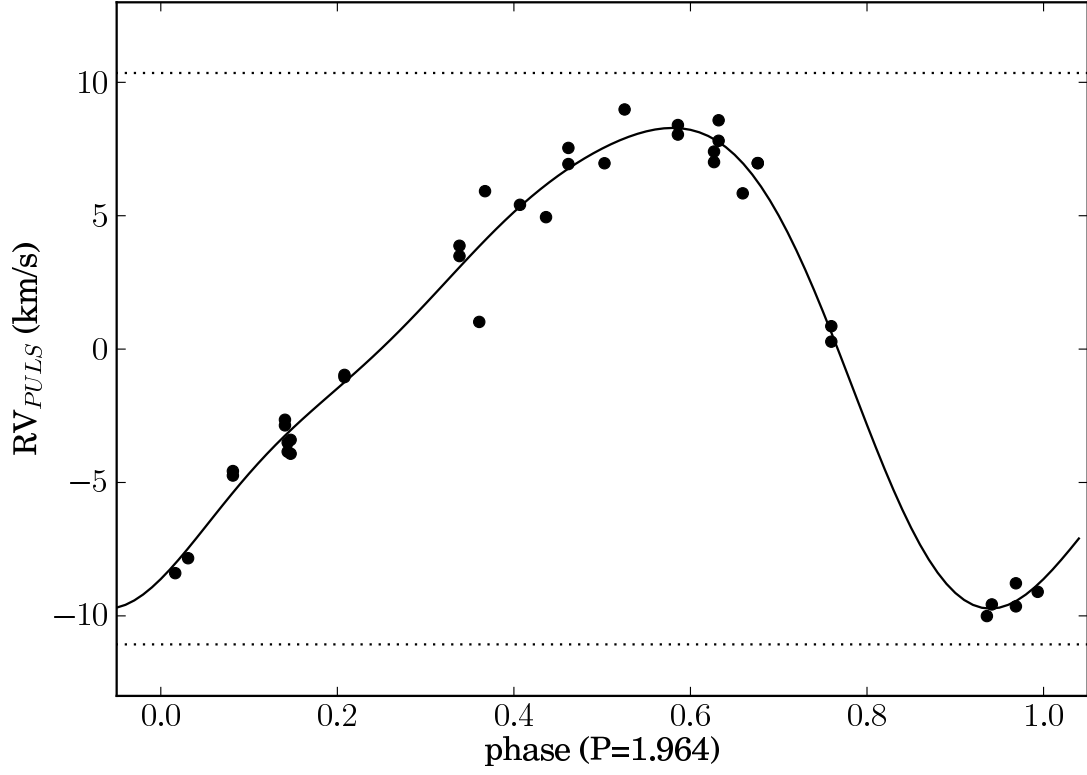


Fig. 2.— Pulsational radial velocity curve of the primary component of the OGLE-LMC-CEP-1718 system. The pulsational phases of the Cepheid are well covered by the observations. The solid curve is a Fourier series fit to the data. The two horizontal dotted lines indicate the radial velocity amplitude of the secondary, longer-period Cepheid in the system.

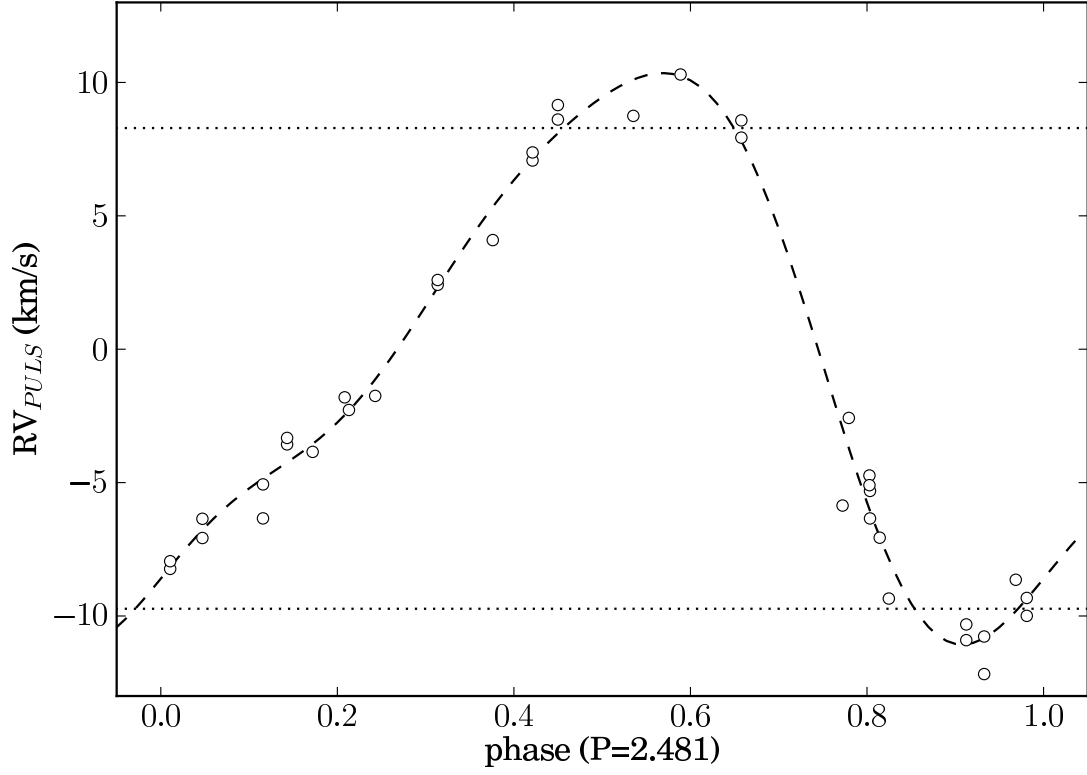


Fig. 3.— Pulsational radial velocity curve of the secondary component of the OGLE-LMC-CEP-1718 system. The data cover the pulsation cycle of the Cepheid very well. The dashed line is a Fourier series fit to the data. The horizontal dotted lines indicate the (smaller) radial velocity amplitude of the primary Cepheid in the system.

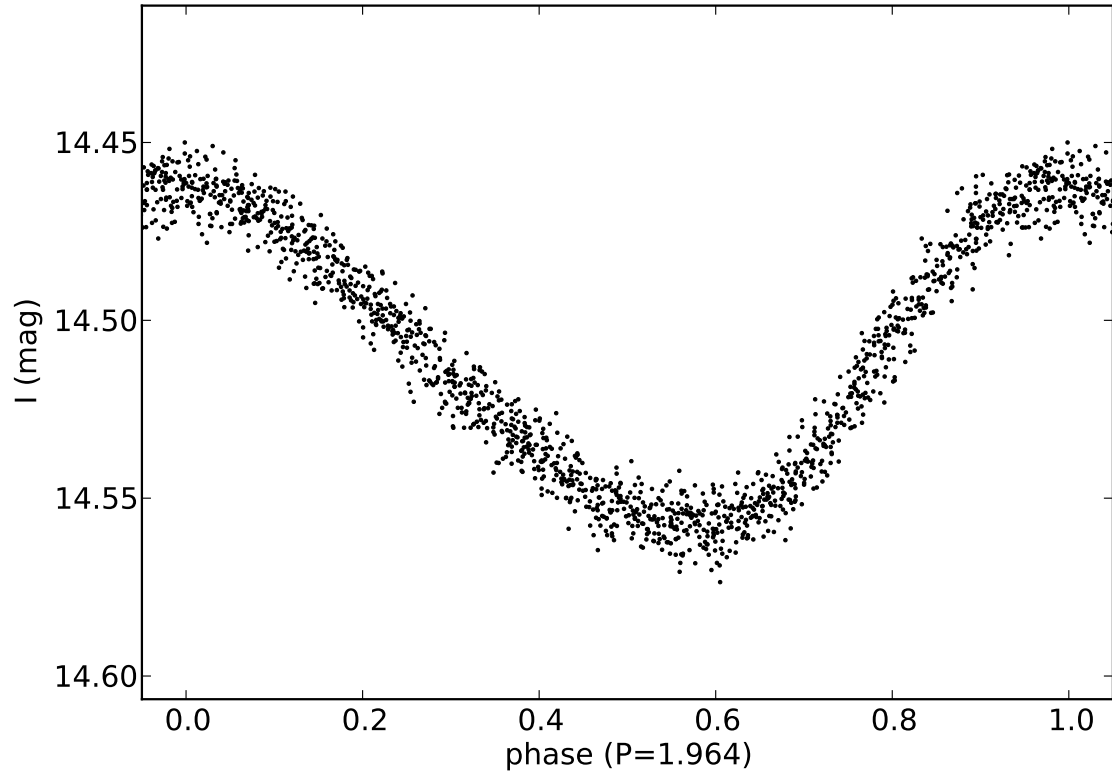


Fig. 4.— Pulsational I-band light curve of the primary component of the OGLE-LMC-CEP-1718 system. The small amplitude and the near-sinusoidal shape of the light curve are typical for Cepheids pulsating in the first overtone mode.

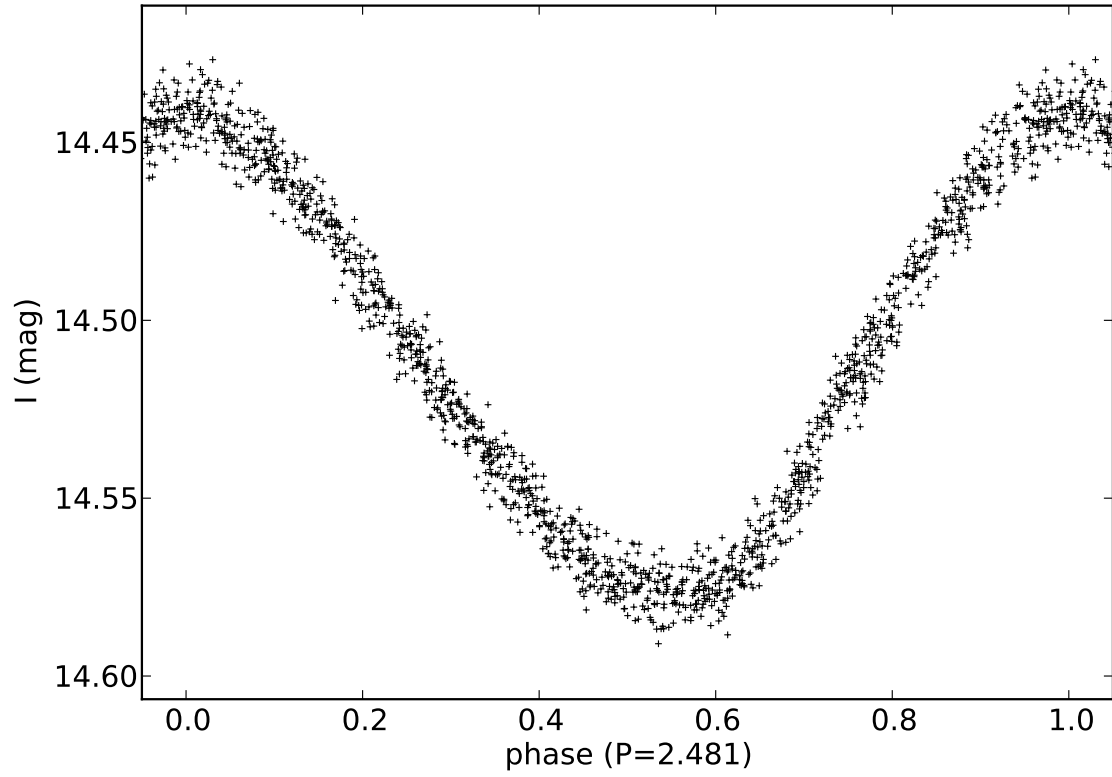


Fig. 5.— Pulsational I-band light curve of the secondary component of the OGLE-LMC-CEP-1718 system. As for the primary component, the light curve amplitude and symmetry suggest that the secondary Cepheid is a first overtone pulsator as well.

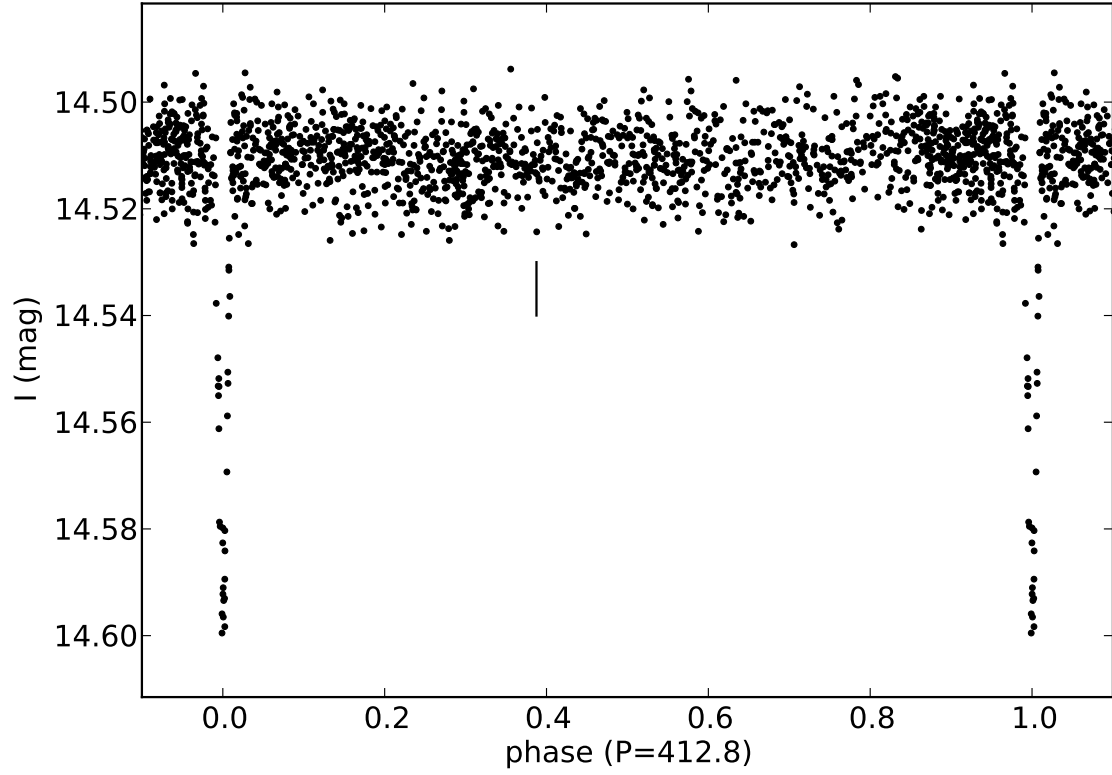


Fig. 6.— Orbital I-band light curve of the OGLE-LMC-CEP-1718 system, with the pulsational variabilities of its two Cepheid components removed. Only the primary eclipse is visible. The bar below the light curve indicates the expected position of the secondary eclipse as estimated from the orbital solution given in Table 2.

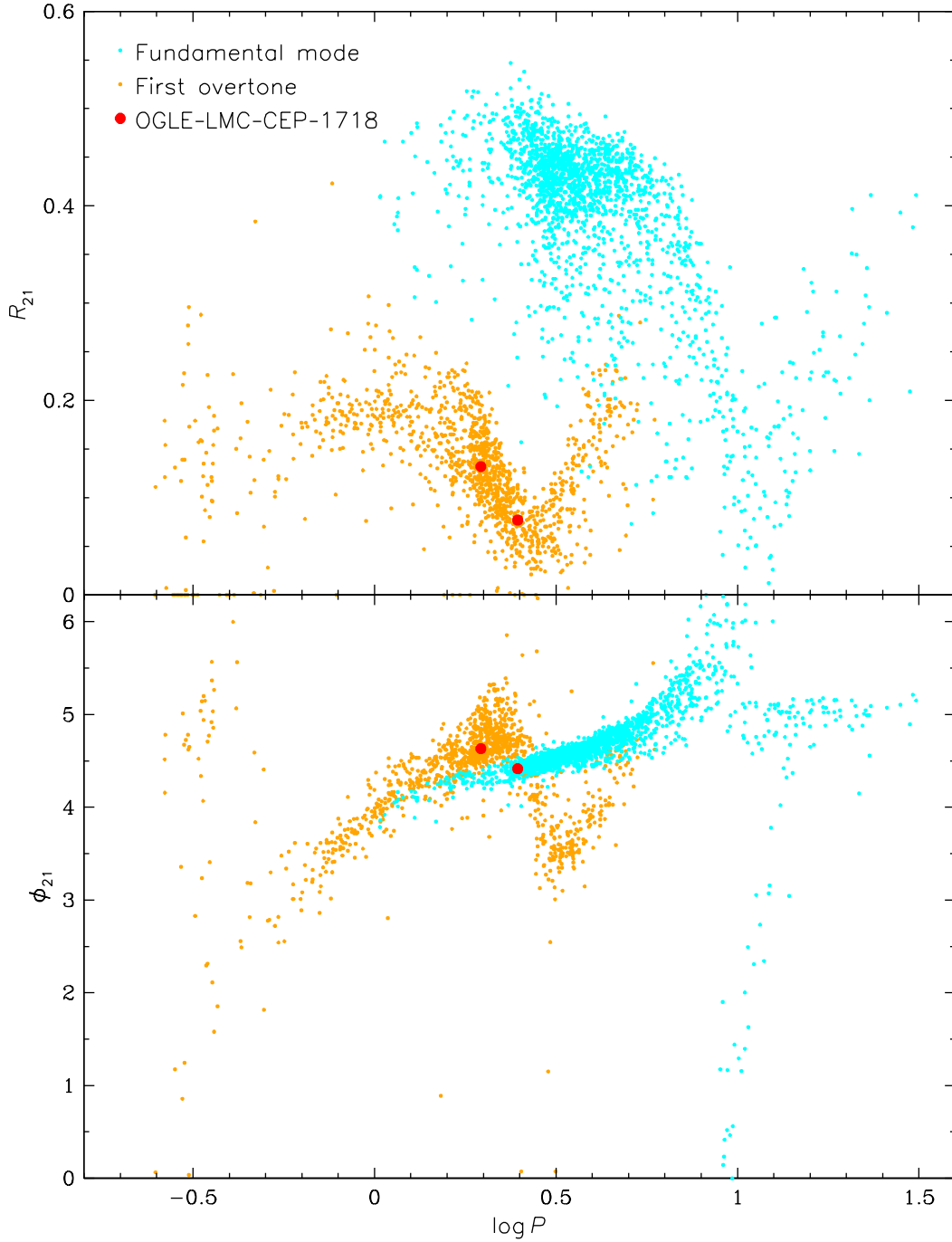


Fig. 7.— Fourier decomposition parameters from the pulsational I-band light curves of the two Cepheids in the OGLE-LMC-CEP-1718 system, plotted against the log of the observed pulsation periods (in days). Both Cepheids clearly lie on the sequence for first overtone pulsators (yellow points; data from Soszynski et al. 2008) in the amplitude-period plot (upper panel). In the lower panel phase-period plane, the mode identification for the secondary ($P=2.48$ day) Cepheid is complicated because it lies in the overlapping part of the first overtone and fundamental mode sequences in this diagram. Its position in the upper panel diagram however allows a very secure identification of its first overtone pulsation mode.

Table 1. Radial velocities of the OGLE-LMC-CEP-1718 system.

HJD	RV_1	RV_2	HJD	RV_1	RV_2	HJD	RV_1	RV_2
5833.7700	227.2	256.7	5965.7124	282.4	214.1	6573.8505 ^a	218.8	269.7
5833.7701	226.7	255.3	6309.7243	278.5	225.7	6577.7492 ^a	217.8	264.8
5833.8898	229.7	257.4	6314.7440	268.2	220.1	6637.5343	233.3	261.4
5833.8898	229.6	258.1	6314.7440	268.4	219.7	6637.5343	232.7	262.0
5836.7729	238.6	262.9	6529.9196 ^a	239.4	273.2	6637.7779	234.2	264.0
5836.7729	238.6	263.1	6554.8613 ^a	230.2	279.3	6637.7779	233.9	264.3
5951.5845	278.4	222.5	6558.8792	234.0	267.7	6637.8685	233.6	265.2
5951.5845	278.7	222.8	6560.7652	234.3	261.1	6637.8685	234.4	265.9
5952.5329	289.1	209.3	6571.7000 ^a	216.9	275.3	6638.5298	216.3	274.6
5952.5329	289.5	210.3	6572.6830 ^a	231.7	265.5	6638.5298	217.2	274.8
5964.5759	279.2	226.8	6572.8131 ^a	233.7	262.0	6638.8675	223.3	280.7
5964.5759	279.8	227.4	6573.6746 ^a	217.1	267.6	6638.8675	223.1	281.3
5965.7124	282.0	212.8	6573.7767 ^a	217.5	269.2			

^aobtained using HARPS data (all the rest – using MIKE data). The radial velocities are in km/s.

Table 2. Orbital solution for CEP-1718.

Parameter	Value
γ (km/s)	248.97 ± 0.15
T_0 (d)	2450697.3 ± 0.9
$a \sin i$ (R_\odot)	452.8 ± 3.5
$q = M_2/M_1$	0.993 ± 0.013
e	0.276 ± 0.013
ω (deg)	308.6 ± 1.8
K_1 (km/s)	28.76 ± 0.25
K_2 (km/s)	28.96 ± 0.30

Table 3. Properties of CEP-1718.

Parameter	Primary	Secondary
pulsation period (d)	1.9636625	2.480917
pulsation mode	FO	FO
mass (M_{\odot})	3.3 ± 0.11	3.28 ± 0.11
radius ^a (R_{\odot})	24.0 ± 1.2	$28.5^{+2.9}_{-1.1}$
orbital period (d)	412.807 ± 0.008	
T_{pri} (d)	2455050.5 ± 0.1	
semimajor axis (R_{\odot})	454.9 ± 3.6	
inclination (deg)	$84.5^{+0.15}_{-0.4}$	

^a The values were calculated using the sum of the radii from our light curve analysis, and the ratio obtained from the period - radius relation for first overtone Cepheids of Sachkov (2002). The errors were estimated independently.